VI. Zagami

Basalt, ~18 kg.

seen to fall

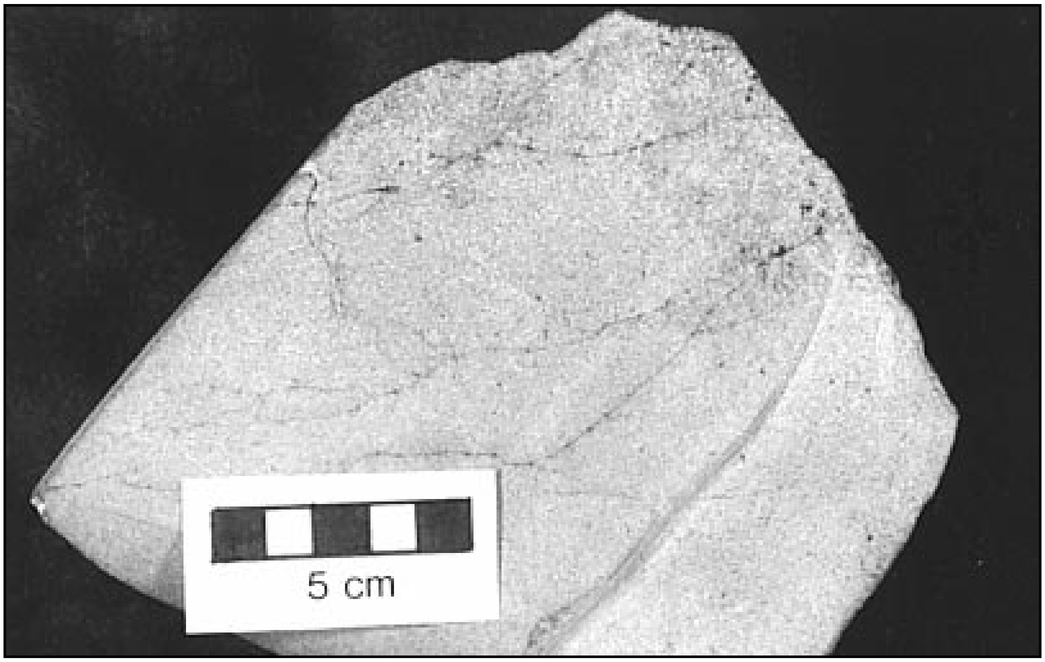

Figure VI-1. *Sample is a 2.8 kg end piece from the collection of Robert Haag. Figure from McCoy et al., 1997. Note variation in texture.*

Introduction

Zagami fell on October 3, 1962 about 0.75 miles from Zagami Rock, Katsina Province, Nigeria (Graham *et al.*, 1985). In 1985, the main mass was with the Geological Survey of Nigeria in Kaduna. About 1988, Robert Haag (meteorite dealer) obtained a large piece of Zagami. Since then, the whole specimen has apparently been cut up and "*distributed*" (*see Processing*).

Both Shergotty and Zagami are texturally and mineralogically similar to terrestrial diabases (although all of the plagioclase has been shocked to maskelynite), but quite distinct petrologically and chemically from the rest of the basaltic achondrites (Stolper *et al.*, 1979). From what is now known about Zagami, it appears to have been made up of more than one lithologiy.

Zagami was the second meteorite found to contain a significant amount of trapped Martian atmosphere (Marti *et al.*, 1995).

Treiman (1993b) noted the apparent coincidence of the falls for Zagami and Chassigny, both on October 3 (*different years*). However, this observation does not agree with the cosmic-ray exposure ages, which are different for these two rocks.

Petrography

Zagami is heterogeneous and apparently contains several different lithologies (figure VI-1). The normal Zagami lithology (NZ) is a basalt similar to Shergotty (Stolper and McSween, 1979; McCoy *et al.*, 1992). In addition, McCoy *et al.* (1995) have studied a dark-mottled-lithology (DML) which makes up ~ 20 % of the large specimen obtained by R. Haag. According to McCoy *et al.*, the DML lithology is separated from the NZ lithology along a sharp, but sometimes irregular boundary (figure VI-1) and is found to contain pockets of shock-melt found to contain Martian atmosphere (Marti *et al.*, 1995). A centimeter-sized piece of distinctly different, Fe-rich material (described below),

Mineral Mode

	Stolper & McSween 1979		McCoy *et al*. 1992				McCoy *et al.* 1993
			fine grain		*coarse grain*		*DN lithology*
pyroxene	76.3	69.7	77.7	74.3	76.0	80.4	13.6
maskelynite	18.8	24.7	17.6	18.8	18.6	10.3	18
mesostasis	1.7	2.6	1.8	3.0	2.1	3.7	8.1
oxides	2.7	2.8	1.5	1.8	2.0	2.6	5.9
sulfides	0.5	0.2	0.6	0.4	04	0.6	1.6
phosphates			0.5	0.6	0.5	1.3	11.4
shock melt			0.1	0.9	0.3	0.9	
fayalite-rich intergrowth							39.9

obtained from David New (*see* Agerkvist and Vistisen, 1993), was originally studied by Vistisen *et al.* (1992), McCoy *et al.* (1993), Wadhwa *et al.* (1993) and McCoy *et al.* (1995).

Normal Zagami exhibits a foliated texture produced by preferential orientation of pyroxene prisms and maskelynite grains (figure VI-2)(Stolper and McSween, 1979; McCoy *et al.,* 1992). It is made up of two portions with different grain size — an average grain size of 0.24 mm for the "fine-grain" portion and 0.36 mm for the "coarse-grained" portion (figures VI-3 and VI-4). The NZ portion of Zagami is cross-cut by glass veins of shock-melt that seem to follow the alignment of pyroxene laths (McCoy *et al.,* 1992; Wadhwa *et al.*, 1993). Plagioclase has been converted to maskelynite *(or plagioclase glass)* by shock.

The Fe-rich, DN lithology of Zagami has been described as a residual melt (McCoy *et al.,* 1993; Wadhwa *et al.,* 1993). McCoy *et al.* describe pigeonite, plagioclase and phosphates as phenocryst phases in DN. Although augite occurs as phenocrysts in NZ, it does not in DN. The compositions of the

Figure VI-2. *Close-up photo of sawn surface fo Zagami illustrating alignment of pyroxene grains. Sample is about 1 cm. across. NASA S94-45980. Photo courtesy of Larry Nyquist.*

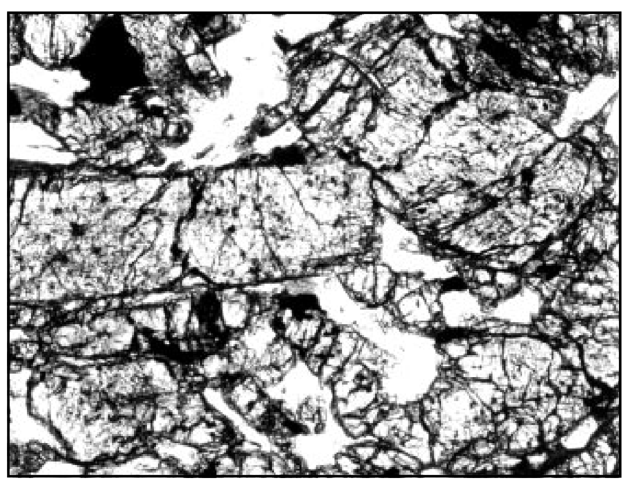

Figure VI-3. *Photomicrograph of thin section of Zagami, illustrating fine-grained basaltic texture. Thin section #991 from University of New Mexico. Field of view 2.2 mm.*

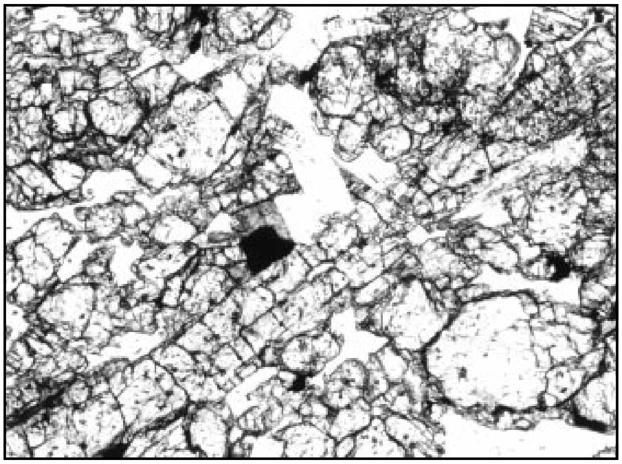

Figure VI-4. *Photomicrograph of thin section of Zagami, illustrating coarser-grained basaltic texture. Thin section #999 from University of New Mexico. Field of view 2.2 mm.*

phases in DN extend the range of composition of phases found in NZ to higher Fe and higher Na. There is also more whitlockite in DN lithology than in NZ and there are minor, relatively large, fluorapatite crystals in DN. Within the DN lithology, there are olivine-bearing intergrowths containing fayalite (Fa_{90-96}), Fe-rich augite and K-rich mesostasis.

Magmatic melt inclusions are found in the Mg-rich cores of the pigeonite grains (Treiman, 1983, 1985, McCoy *et al.*, 1992). Several of these melt inclusions include amphibole (see below).

Mineral Chemistry

Pyroxene**:** Easton and Elliot (1977) reported the compositions of pyroxene separates from Zagami. Stolper and McSween (1979) studied the pyroxene zoning (figure VI-5). Brearley (1991) studied the subsolidus exsolution and microstructure of pyroxenes in Zagami. Treiman and Sutton (1992) and Shearer and Brearley (1992) studied the cores and rims of Zagami pyroxenes by synchrotron and ion microprobe techniques. Wadhwa *et al.* (1994a) determined the REE and minor element contents (Y, Sc, Ti, Cr, and Zr) of pyroxenes (figure IX-14). The high-Ca pyroxenes contain about 10X REE abundance compared to low-Ca pyroxene, but with similar LREE depleted pattern.

Plagioclase**:** Easton and Elliot (1977) reported the composition of "feldspar/glass" in Zagami as $An_{51.5}Ab_{46.2}Or_{2.3}$. Stolper *et al.* (1979) determined that

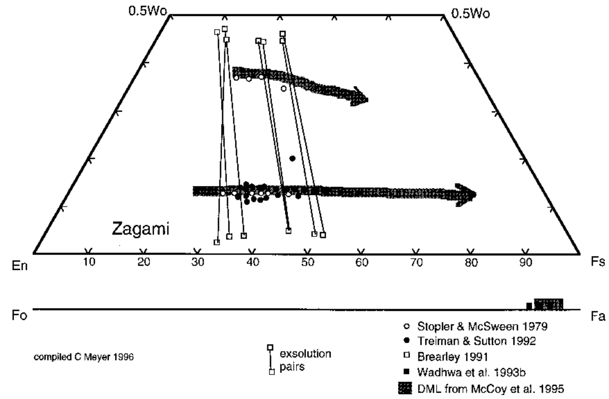

Figure VI-5. *Composition diagram for pyroxenes in Zagami meteorite. Data compiled from Stolper and McSween (1979), Treiman and Sutton (1992), Brearley (1991), Wadhwa et al. (1993b) and McCoy et al. (1995).*

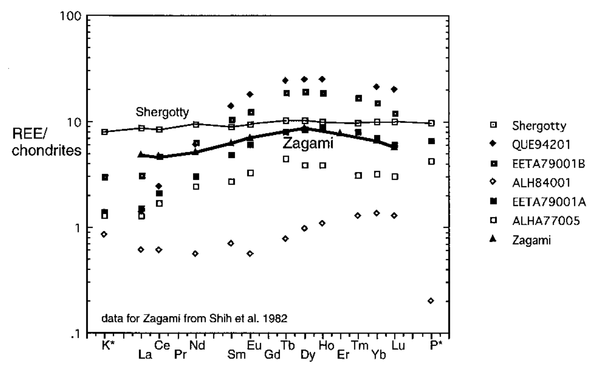

Figure VI-6. *Chondrite normalized composition diagram for rare earth elements in Zagami meteorite. The data for Zagami are from Shih et al. (1982).*

individual maskelynite grains are zoned from $An_{57}Ab_{42}Or_{1}$ to $An_{43}Ab_{53}Or_{4}$. Langenhorst *et al.* (1991) studied the index of refraction and composition to determine the shock pressure. Jones *et al.* (1985b) studied the zoning of minor elements in maskelynite with a proton microprobe technique. Mikouchi *et al.* (1998) find that Zagami maskelynite is not a diaplectic glass, but is a melt glass.

Amphibole**:** Treiman (1985a) reported hydrous amphibole in melt inclusions in Zagami. One grain of amphibole has been analyzed for D/H ratio by Watson *et al.* (1994c).

Phosphates**:** Wadhwa *et al.* (1994a) found that the REE pattern for whitlockite was similar to that of the bulk sample. Wang *et al.* (1998) determined the Raman spectra of both apatite and whitlockite.

Apatite**:** Watson *et al.* (1994a) studied a large apatite

Table IV-1. Chemical composition of Zagami.

	Treiman 86	Laul 72	Easton 77	Burger 89	Smith 84	Shih 82	Ma 81	Ma 82	Haramura 95	Stolper 79	McCoy 92
weight	*0.1-0.2 g*						*(Irving)*	*40 mg*			
SiO2 %			50.9 (d)						50.52 (d)	50.8 (e)	51.2
TiO2			0.73 (d)	0.77 (a)	0.8 (b)			0.8 (b)	0.84 (d)	0.77 (e)	0.81
Al2O3			5.7 (d)		6.4 (b)			6.4 (b)	6.27 (d)	5.67 (e)	6.19
FeO			17.3 (d)		19 (b)			19 (b)	18.03 (d)	18 (e)	18.2
MnO			0.5 (d)		0.5 (b)			0.502 (b)	0.44 (d)	0.5 (e)	0.55
CaO			10.5 (d)		10.6 (b)			10.6 (b)	9.57 (d)	10.8 (e)	10.7
MgO			11.4 (d)		11.1 (b)			11.1 (b)	12.14 (d)	11 (e)	10.4
Na2O			1.2 (d)		1.21 (b)			1.21 (b)	0.13 (d)	0.99 (e)	1.29
K2O			0.1 (d)		0.14 (b)			0.14 (b)	0.08 (d)	0.14 (e)	0.13
P2O3			0.48 (d)						0.46 (d)		0.58
sum			**98.81**						**98.45**	**98.67**	**100.05**
Li ppm						3.82 (c)					
C											
F											
S											
Cl											
Sc					53 (b)		57 (b)	53 (b)			
V					312 (b)			312 (b)			
Cr			2600 (d)		1984 (b)			1984 (b)	1026 (d)		
Co					36 (a)		37 (b)	36 (b)			
Ni	90 (a)				50 (b)		67 (b)				
Cu											
Zn	63.8 (a)	55 (a)			62 (a)						
Ga					14 (a)						
Ge	0.78 (a)										
As					0.046 (a)						
Se	0.32 (a)	0.33 (a)			0.32 (a)						
Br	0.79 (a)										
Rb	9.56 (a)	6 (a)			5.7 (a)	5.69 (c)					
Sr					46	45.9 (c)					
Y				10.6 (a)							
Zr				58.2 (a)							
Nb											
Mo											
Pd ppb	1.79 (a)										
Ag ppb	14.2 (a)	37 (a)			31						
Cd ppb	179 (a)	71 (a)			61 (a)						
In ppb	26.6 (a)	22.2 (a)			22 (a)						
Sb ppb	5.2				12 (a)						
Te ppb	2.2 (a)				1 (a)						
I ppm											
Cs ppm	0.367 (a)	0.336 (a)			0.38 (a)						
Ba				27.4 (a)	25 (b)	25.3 (c)					
La					0.9 (b)	1.6 (c)	2.07 (b)	0.9 (b)			
Ce						3.75 (c)					
Pr											
Nd						2.89 (c)					
Sm					0.76 (b)	1.17 (c)	1.42 (b)	0.76 (b)			
Eu					0.44 (b)	0.476 (c)	0.51 (b)	0.44 (b)			
Gd											
Tb					0.22 (b)		0.34 (b)	0.22 (b)			
Dy					1.7 (b)	2.66 (c)		1.7 (b)			
Ho											
Er						1.6 (c)					
Tm											
Yb					0.98 (b)	1.38 (c)	1.45 (b)	0.98 (b)			
Lu					0.13 (b)	0.201 (c)	0.26 (b)	0.13 (b)	**Lee & Halliday 97**		
Hf				1.6 (a)	1.7 (b)		1.9 (b)	1.7 (b)	1.946 (c)		
Ta				0.19 (a)	0.2 (b)		0.22 (b)	0.2 (b)			
W ppb				800 (a)					445 (c)		
Re ppb	0.035 (a)										
Os ppb	0.119 (a)										
Ir ppb	0.033 (a)	0.1 (a)									
Au ppb	1.76 (a)	2.1 (a)			2.2 (a)						
Tl ppb	11.7 (a)	11 (a)			12 (a)						
Bi ppb	1.64 (a)	1.1 (a)			5.1 (a)				**Chen 86**		
Th ppm							0.27 (b)		0.367 (c)		
U ppm	0.094 (a)				0.154 (a)				0.091 (c)		

technique (a) RNAA, (b) INAA, (c) Isotope dilution mass spec., (d) wet, (e) elec. probe, fused sample

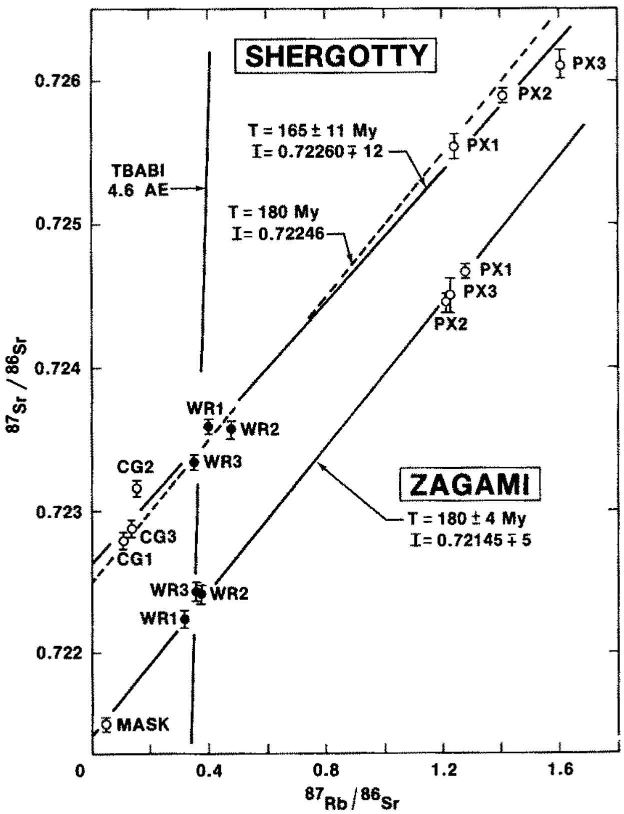

Figure VI-7. *Rb-Sr isochron diagram for Zagami and Shergotty meteorites. This is figure 3a in Shih et al. (1982), GCA **46**, 2323.*

grain in the residual melt portion of Zagami (DN) (Vistisen *et al.*, 1992; McCoy *et al.*, 1993; Wadhwa *et al.*, 1993b) and found that it contained 0.3-0.4 wt % H_2O with a high D/H ratio.

Sulfides: The sulfide phase is pyrrhotite.

Oxides: Titanomagnetite occurs as subhedral grains and has minor ilmenite exsolution.

Fayalite: Fayalite (Fa_{90-96}) occurs as part of "intergrowth" assemblage in late-stage DN lithology. Wadhwa *et al.* (1993) reported that this late-stage olivine was considerably enriched in Ti, Zr, Y and REEs. Olivine was first noted in the Mössbauer spectra of Vistisen *et al.* (1992).

Glass: Glass veins (pseudotachylite) and "glass pods" in Zagami were analysed by McCoy *et al.* (1992) and Marti *et al.* (1995).

Whole-rock Composition

Easton and Elliot (1977) reported the bulk composition of Zagami and noted a trace of bound water. Stolper

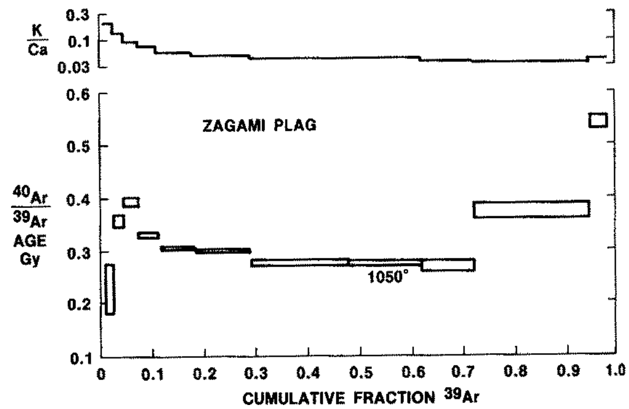

*Figure VI-8. Ar plateau diagram for Zagami meteorite from Shih et al. (1982), GCA **46**, 2330.*

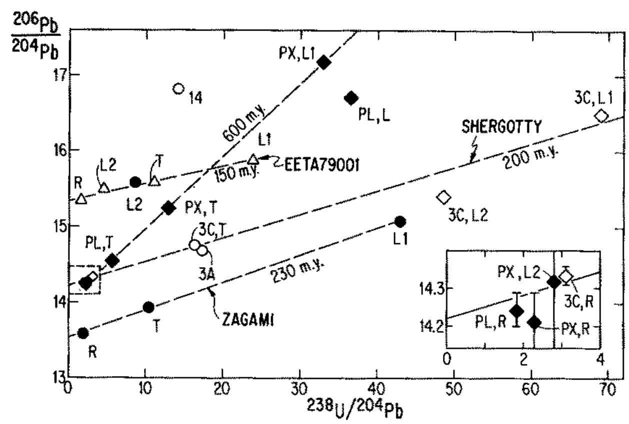

*Figure VI-9. U-Pb isochron diagram for Zagami meteorite from Chen and Wasserburg (1986c), GCA **50**, 959.*

and McSween (1979), McCoy *et al.* (1991, 1992) and Haramura (1995a) also reported bulk analyses (table VI-1). Trace elements have been determined by Shih *et al.* (1982) (figure VI-6). Smith *et al.* (1984) noted that there was a wide range of absolute REE abundances (*e.g.* La = 0.9 to 1.9 ppm), as reported by various investigators. Gibson and Moore (1983) determined 1850 ppm S. Karlsson *et al.* (1992) determined 430 ppm H_2O.

Radiogenic Isotopes

Shih *et al.* (1982) originally determined an age of 180 ± 4 Ma with $I^{87}Sr/^{86}Sr$ = 0.72145 ± 5 using Rb-Sr (figure VI-7)(λ_{Rb}=1.39 x 10^{-11} $years^{-1}$). They also reported an argon plateau age of ~260 Ma for the plagioclase (figure VI-8). Nyquist *et al.* (1995) determined Rb-Sr isochrons of 186 ± 5 Ma and 183 ± 6 Ma for the fine and coarse grained portions of Zagami and found a slight difference in the initial Sr of the two lithologies. Nyquist *et al.* (1995) determined the Sm-Nd isochron using data from both lithologies to give an age of 180

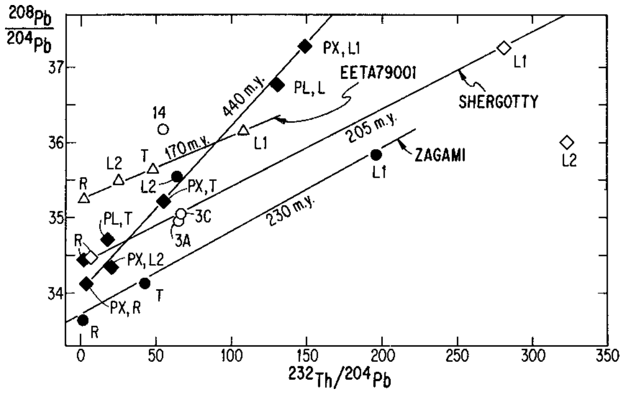

Figure VI-10. *U-Th-Pb diagram for Zagami meteorite from Chen and Wasserburg (1986c), GCA* ***50****, 959.*

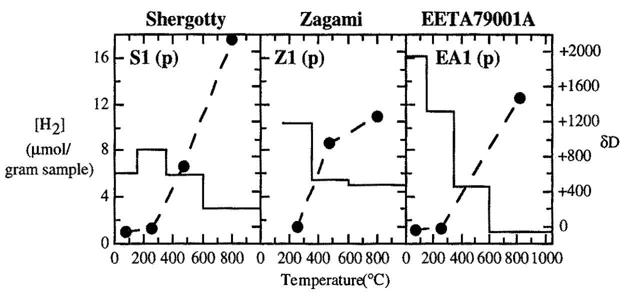

Figure VI-11. *Hydrogen isotope composition of water released from Shergotty, Zagami and EETA79001 meteorites. This is a copy of figure 3 in Leshin et al. (1996), GCA* ***60****, 2641.*

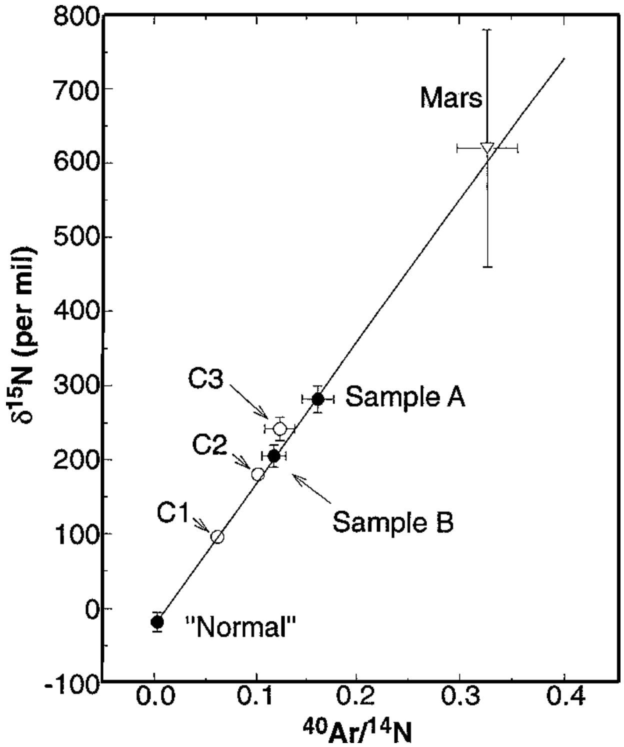

Figure VI-12. *Nitrogen isotopic composition and N/Ar ratio of gas released from glass inclusions in Zagami meteorite compared with data from Viking (Mars) and EETA79001 (C1-3). This is figure 3 in Marti et al. (1995), Science* ***267****, 1983.*

± 37 Ma. Bogard and Garrison (1998) recalculate the Ar-Ar age as 209 Ma.

By leaching "whole rock" samples of Zagami, Chen and Wasserburg (1986a) obtained a U-Pb "isochron age" of 230 ± 5 Ma (figure VI-9) and a Th-Pb "isochron" of 229 ± 8 Ma (figure VI-10). These leach experiments probably attack the phosphates in the sample, *which may have already been altered on Mars*.

Cosmogenic Isotopes and Exposure Ages

Bogard *et al.* (1984b) measured cosmic-ray produced ^{3}He, ^{21}Ne and ^{38}Ar and determined the exposure age to be ~2.5 Ma. Pal *et al.* (1986) determined an exposure age of 5.3 ± 3.5 Ma using ^{10}Be. Eugster *et al.* (1996) derived an exposure age for Zagami of 2.8 ± 0.2 Ma and concluded that Zagami was *"ejected from Mars simultaneously with the other basaltic shergottites Shergotty and QUE94201."*

Other Isotopes

Clayton and Mayeda (1983, 1996) reported the oxygen isotopes for Zagami. Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Zagami was enriched in ^{17}O, indicating that the past hydrosphere on Mars was from a different reservoir than the lithosphere. Romanek *et al*. (1996) reported additional oxygen isotope data, using a new laser technique.

Watson *et al.* (1994c) reported the deuterium contents of hydrous amphiboles and a large apatite in Zagami. Leshin *et al*. (1996) found the water released from Zagami had high D/H ratios (figure VI-11).

Fallick *et al.* (1983), Wright *et al.* (1986), Jull *et al.* (1996b) and Grady *et al.* (1997) have reported measurements of carbon isotopes from Zagami. Jull reported the measurements with low ^{14}C (*a measure of terrestrial contamination*) have $\delta^{13}C$ = -20 ‰. Grady *et al.* found C and N released above 600 deg. C was of magmatic origin with $\delta^{13}C$ ~= -26 ‰ and $\delta^{15}N$ ~=–5 ‰. Grady *et al*. reported that the carbon and nithrogen released below about 600 deg. C, was probably from terrestrial organic contamination.

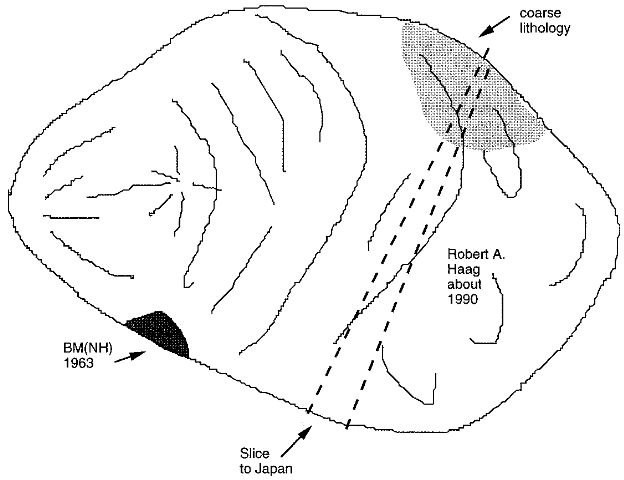

Figure VI-13. *This sketch of Zagami was kindly provided by Robert A. Haag who witnessed the sawing of the sample in 1988. The "coarse lithology" is referred to in the text as the DML lithology. The sample obtained by the British Museum is known as normal Zagami (NZ) and seems to be representative of the main mass.*

Blichert-Toft *et al.* (1998) determined the isotopic ratio of Hf, Harper *et al.* (1995) determined the isotopic ratio of Nd, Lee and Haliday (1997) determined the isotopic ratio of W, and Molini-Velsko *et al.* (1986) reported normal isotopic composition for Si.

Chen and Wasserburg (1986a) reported the Pb isotopes in Zagami and concluded that the parent body (Mars) was enriched in ^{204}Pb and other volatiles.

Marti *et al.* (1995) reported the isotopic signatures of nitrogen, argon and xenon in shock-melted glass "pockets" in Zagami and found the same characteristics (heavy nitrogen) as for the glass from EETA79001 and Viking (figure VI-12). This, then, is the second Martian meteorite (besides EETA79001) found to contain trapped (modern) Martian atmosphere.

Shock Effects

Stöffler *et al.* (1986) determined the shock pressure and temperature experienced by Zagami was 31 GPa and 220^{o}C. Marti *et al.* (1995) studied the shock-melted pockets in the mottled lithology. Langenhorst *et al.* (1991) carefully studied the maskelynite (see above). Mikouchi *et al.* (1998) report annealing experiments on "maskelynite' from Zagami and find that it is not a diaplectic glass, but rather a melt glass.

Experiments

Dreibus *et al.* (1996a) have reported experiments on leaching Zagami, showing that the phosphates readily dissolve, releasing many trace elements to the solution.

Stolper and McSween (1979) and McCoy and Lofgren (1996) have performed crystallization experiments to determine the phase equilibria and cooling history.

The infrared spectra of various lithologies of Zagami has been measured by Hamilton and Christensen (1996), Wasch and Schade (1996) and Hamilton *et al.* (1997)(figure II-13). Wang *et al*. (1998) have used Raman spectroscopy to determine the mineralogical mode.

Table VI-2. Petrophysical properties of SNC meteorites.
(from Terho 1995)

Meteorite	NRM	χ_o	Q	ρ	Ref.
Chassigny	19	14	3.22	3319	3
Nakhla	13	182	0.18		1,2
Governador Valadares	51	167	0.76		1,2
Shergotty A-B	41	127	0.81		1,2
Shergotty C	361	112	8.1		1,2
Zagami fc	260	100	6.5		1,2
Zagami	4069	54	188	3071	3
ALHA77005,77	32	645	0.12		1,2
ALHA77005	23	347	0.17		4
EETA79001 A	17	88	0.48		1,2
EETA79001	30	47	1.6		4
EETA79001,183	24	63	0.95	3124	3

NRM = natural remanent magnetization (10^{-6} Am^2/kg)
χ_o = initial susceptibility (10^{-8} m^3/kg)
Q = Koenigsberger ratio
ρ = density (kg/m^3)
References: 1) Cisowski 1985, 2) Cisowski 1986, 3) Terho *et al.* 1993, 4) Collinson 1986.

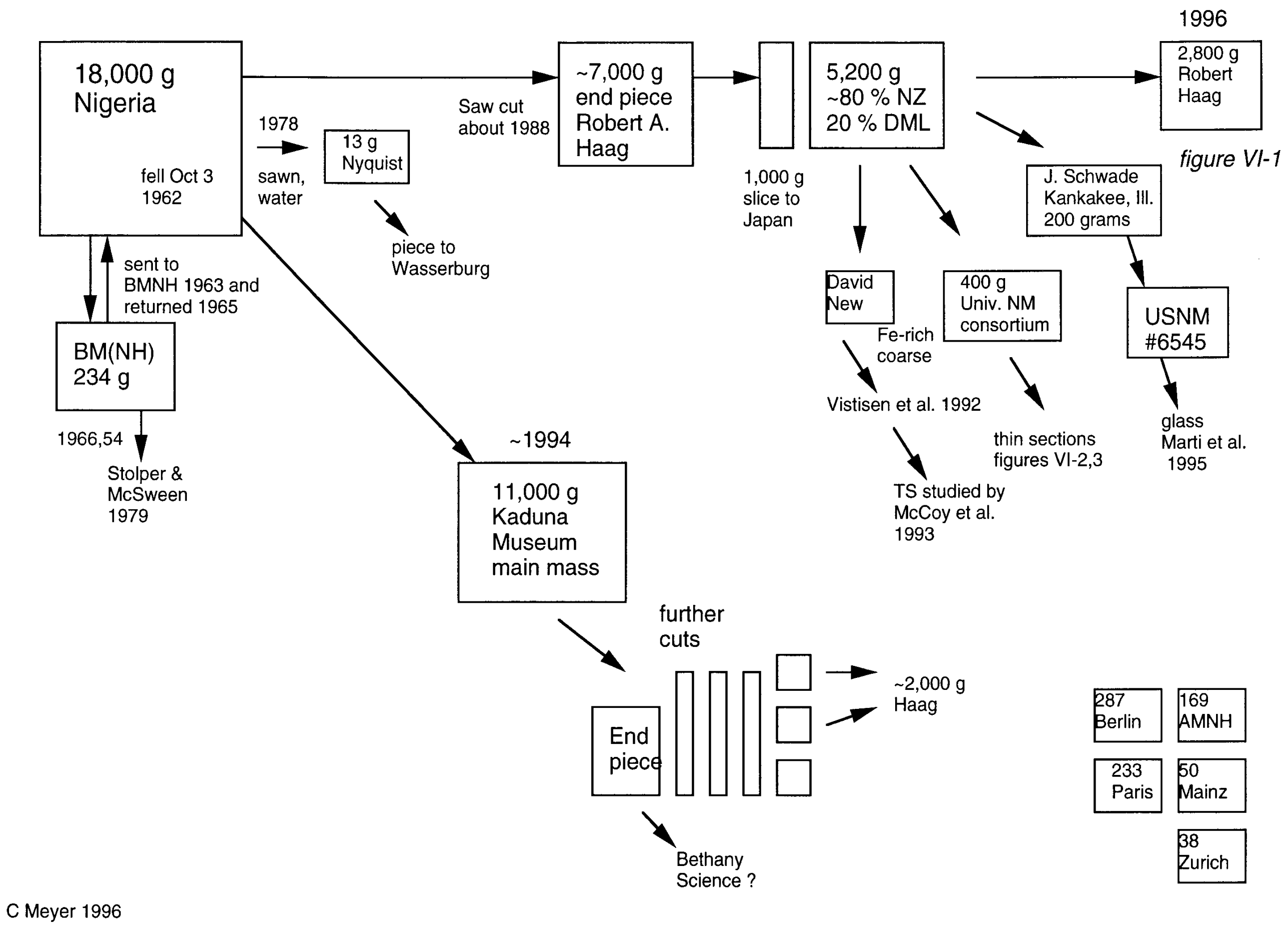

Figure VI-14. *This diagram tries to illustrate what is known about the cutting and distribution of this large Martian meteorite — after it became known that it was from Mars. (If you are a rock, you shouldn't let anyone know that you came from Mars.)*

The magnetic properties of Zagami have been studied by Cisowski (1985, 1986) and Terho *et al.* (1996, 1998) (table VI-2).

Processing

In 1963, the main mass of Zagami was sent to the British Museum of Natural History. In 1965, it was returned to Kaduna, Nigeria. In 1985, the meteorite catalog of Graham *et al.* showed that the BM(NH) had pieces weighing 234 grams - with the main mass in Kaduna. In 1978, Nyquist obtained a 13 gram piece from Nigeria, that was sawn on three sides illustrating a gradational contact from fine to coarse grain basalt (figure VI-2), including a thin black glass vein (Nyquist, personal commincation).

About 1988, the main mass was sawn to reveal the interior (?). Robert Haag (meteorite dealer) was apparently able to trade *"a complete meteorite collection"* for a sizable portion of the Zagami stone (Norton, 1994). Haag (1991) illustrated a piece 158 x 165 x 70 mm weighing 2.8 kg. partially covered by fusion crust. Since 1991, the main mass in Kaduna has apparently been further cut up and "*distributed*" (figures VI-13 and VI-14) (Haag, personal communication).

During his visit to Nigeria, Haag met the man who witnessed the fall (Haag, 1991). *"He was trying to chase the cows out of his corn field when he heard a tremendous explosion and was buffeted by a pressure wave. Seconds later, there was a puff of smoke and a thud, as something buried itself in the soft dirt only ten feet away. Terrified that it was an artillery shell or bomb, the man waited for a few minutes before going to investigate. What he saw was a black rock at the bottom of a two-foot hole. The local commissioner was summoned and the specimen was recovered and sent to the provincial capital, where it was placed in the* *museum."*

McCoy *et al.* (1992) reported on two pieces weighing 19.5 grams (coarse grain) and 354 grams (fine grain) that were used for a consortium study led by Tim McCoy and Klaus Keil. The smaller piece is a sawn slab, 5 x 3 x 0.4 cm and contained "glassy pockets". The larger piece is roughly cubic 5 cm on a side, with a glassy fusion crust on one side.

McCoy *et al.* (1995) reported examination of a ~910 cm^2 of sawn surface area of Zagami which *"revealed that DN was not present in the normal Zagami (NZ) lithology described by (McCoy et al., 1992; Treiman and Sutton, 1992), but rather in a volumetrically significant lithology termed the dark, mottled lithology (DML). DML occupies ~20% of Zagami and borders NZ along a sharp, but sometimes irregular, boundary."*

The original piece of the DN lithology (~1 cm) was obtained by Vistisen and coworkers from David New (meteorite dealer). All four Zagami lithologies (NZ, DML, DN and melt pockets) are present in Smithsonian sample USNM 6545 (McCoy, personal communication).